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A Proposed Qualitative Framework for Heterogeneous Burning of Metallic Materials: The 'Melting Rate Triangle'

ABSTRACT: This paper presents a proposed qualitative framework to discuss the heterogeneous burning of metallic materials, through parameters and factors that influence the melting rate of the solid metallic fuel (either in a standard test or in service). During burning, the melting rate is related to the burning rate and is therefore an important parameter for describing and understanding the burning process, especially since the melting rate is commonly recorded during standard flammability testing for metallic materials and is incorporated into many relative flammability ranking schemes. However, whilst the factors that influence melting rate (such as oxygen pressure or specimen diameter) have been well characterized, there is a need for an improved understanding of how these parameters interact as part of the overall melting and burning of the system. Proposed here is the 'Melting Rate Triangle', which aims to provide this focus through a conceptual framework for understanding how the melting rate (of solid fuel) is determined and regulated during heterogeneous burning. In the paper, the proposed conceptual model is shown to be both (a) consistent with known trends and previously observed results, and (b) capable of being expanded to incorporate new data. Also shown are examples of how the Melting Rate Triangle can improve the interpretation of flammability test results. Slusser and Miller previously published an 'Extended Fire Triangle' as a useful conceptual model of *ignition* and the factors affecting ignition, providing industry with a framework for discussion. In this paper it is shown that a 'Melting Rate Triangle' provides a similar qualitative framework for *burning*, leading to an improved understanding of the factors affecting fire propagation and extinguishment.

KEYWORDS: heterogeneous burning, melting, heat transfer, rate-limiting mechanism, model

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Introduction

This paper presents a proposed conceptual framework for analysis and discussion of the many parameters that affect the melting rate of a solid metallic material during heterogeneous burning. The paper provides a description of the proposed model, the Melting Rate Triangle, and shows that it is consistent with known trends in experimental data. Potential applications are also described, including in the analysis of results from standardized flammability tests and also in the use of this test data in industrial scenarios.

Background

The regression rate of the melting interface (RRMI) is defined as the velocity at which the external (visible) boundary of the solid/liquid interface (SLI) proceeds along the test specimen during a standard promoted ignition test for metal flammability. The RRMI is closely related to the melting rate of solid fuel and is thus a highly relevant parameter relating to the heterogeneous burning of metallic materials. RRMI is often used as a secondary indicator of relative flammability, especially in distinguishing between metallic materials with the same threshold pressure [1]. Therefore, RRMI is an important parameter within metal flammability testing and oxygen system fire safety, and any further insight into the factors affecting RRMI is relevant and valuable. In a significant contribution to the understanding of metallic material performance in oxygen service, Slusser and Miller defined the "Extended Fire Triangle," [2] which described the many factors affecting the *propensity for ignition*. The analysis was qualitative, but provided a highly useful conceptual framework within which existing and future knowledge could be incorporated. In a similar way, this paper presents the *Melting Rate Triangle*, which aims to provide a conceptual framework to improve the understanding of the factors affecting RRMI.

RRMI is known to be dependent on many factors, including specimen shape, size, composition, configuration and orientation, oxygen pressure and concentration, and many other parameters [3-6]. In work presented concurrently by Ward and Steinberg [7], it is shown that heat transfer across the SLI is the mechanism that limits melting and burning. Further, the heat transfer process is shown specifically to be limited by the available contact surface area for heat transfer between the burning droplet and the solid metal rod.

In this paper, the process of heat transfer across the SLI is considered in a broader context and it is compared with the well-known trends regarding RRMI. Arguably the two most characterized trends observed for burning cylindrical metallic rods are that as (1) oxygen pressure increases and/or (2) test specimen diameter decreases, RRMI increases [3-6, 8, 9]. Significantly, variations in SLI shape and surface area do not account for either of these trends. For cylindrical rods burning in an upward-burning configuration in normal gravity, the SLI shape is independent of pressure and is generally assumed to remain planar and perpendicular for all pressures. This means RRMI can vary with test pressure but without any alteration of the SLI shape (or surface area). Also, whilst the total SLI surface area clearly changes with rod diameter, this does not account for the observed dependence of RRMI on diameter because (for cylindrical rods in upward-burning configurations in normal gravity) the SLI surface area and rod cross-sectional area are equal for all rod sizes. In this way, the dependency of RRMI on both pressure and diameter indicates that, while heat transfer across the SLI surface area is rate-limiting for RRMI, there are other parameters that strongly affect melting and burning. The conceptual framework for discussion of heterogeneous burning presented in this paper is therefore intended to provide a holistic view of the system that is consistent with both the rate-limiting mechanism and also the important influence (on RRMI) of other factors including pressure and specimen diameter.

The Melting Rate Triangle

The Melting Rate Triangle is a conceptual representation of the many factors that affect RRMI during the heterogeneous burning of cylindrical metallic rods. In constructing the Melting Rate Triangle, self-sustained heterogeneous burning is considered as a three-part process by which:

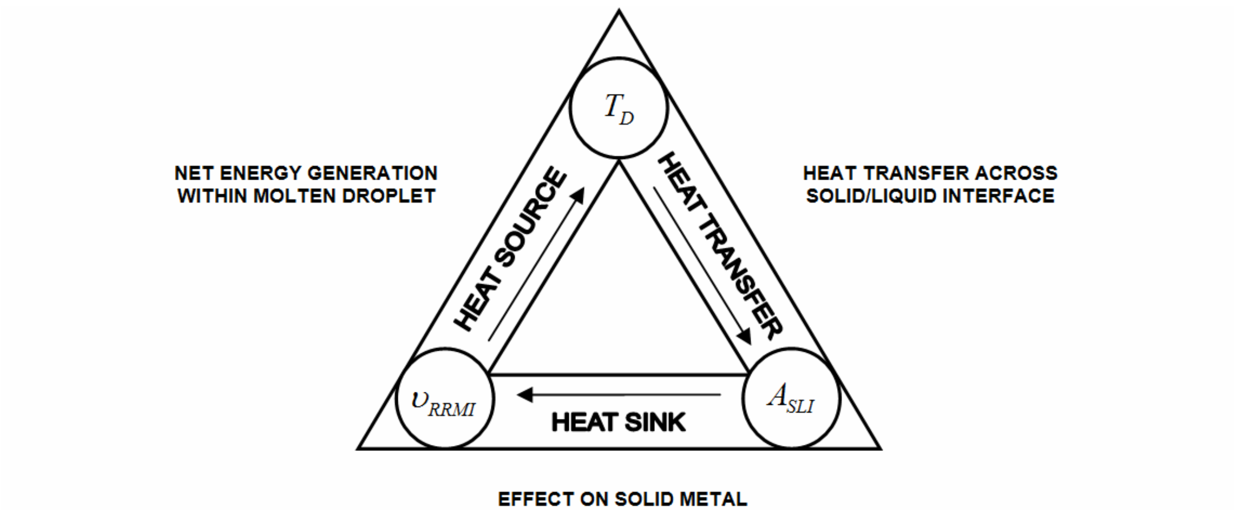
1. Conditions within the burning droplet such as extent of reaction, oxygen availability, and heat of combustion (and many other factors) determine the heat flux input into the SLI, which represents the *'potential'* of the burning droplet to cause melting of the solid. In the context of the Melting Rate Triangle, this process is referred to as *'Heat Source'*.

2. The heat flux from the burning droplet is transferred across the surface area of the SLI, which determines the total heat transfer rate into the solid metal. In the Melting Rate Triangle, this is referred to as *'Heat Transfer'*.

3. Heat transferred to the solid metal causes melting at a rate determined by the cross-sectional area, material properties and initial temperature of the solid test specimen, which results in the observed RRMI. This process is referred to as *'Heat Sink'*.

In this way, the RRMI can be influenced by parameters that relate to *any* of the three processes, by, for example, (1) factors that alter the heat flux that is produced within the burning droplet (changes in the *'potential'* to cause melting), (2) the surface area of the SLI, which limits the amount of heat flux that enters the solid, or (3) altered energy requirements for melting the solid. This is consistent with heat transfer across the SLI being the rate-limiting mechanism, but also implies that any known (or unknown) factors that influence other aspects of the burning system may also affect RRMI. The Melting Rate Triangle incorporating these processes is presented in Fig. 1. The Melting Rate Triangle was specifically developed to represent burning iron and it likely applies generally for heterogeneously burning metallic materials.

The three sides of the Melting Rate Triangle represent the three basic processes of heterogeneous burning (as defined previously) and the three corners represent critical parameters (circled). The critical parameters are the maximum droplet temperature, T_D, the surface area of the SLI, A_{SLI}, and the RRMI, υ_{RRMI}. During self-sustained burning, the heat flow and the interpretation of the model proceed in a clockwise direction. The critical parameters have been highlighted as they each help relate the preceding process to the next. These processes and critical parameters are described in more detail in the following sections.



PROCESS	PARAMETER	IMPORTANT FACTORS
HEAT SOURCE	**Droplet Temperature, T_D**	**Heat Generation:** • Fuel mass flow rate: f(υ_{RRMI}, density, ρ, cross-sectional area, S) • Extent of reaction: f(oxygen pressure, concentration, flow conditions, absorption, solubility, transport...) • Heat of Combustion • Alloying elements, contaminants
		Heat Loss: • Bulk transport (dripping) • Loss to surroundings
HEAT TRANSFER	Heat flux from molten droplet, $\dot{q}$	$\dot{q} = \frac{\kappa_{eff}}{L}(T_D - T_M)$ • Solid melting temperature, T_M • Effective heat transfer coefficient between droplet and solid, K_{eff} • Heat transfer path length within droplet, L
	Solid/Liquid Interface (SLI) Shape and Surface Area, A_{SLI}	In some cases, $A_{SLI} \neq S$, consider: • Orientation (except in microgravity) • Cross-section shape • Surface finish (threaded, etc.) • Configuration (sheet, rod, mesh) • Gravity level • Precession, helical motion (in microgravity)
HEAT SINK	**Regression Rate of the Melting Interface, υ_{RRMI}** (melting rate)	$\upsilon_{RRMI} = \frac{\dot{q}}{\left[\rho \cdot (C_P(T_M - T_0) + \lambda)\right]} \cdot \frac{A_{SLI}}{S}$ • Initial temperature, T_0 • Cross-sectional area, S • Surroundings and boundary conditions • Specific heat, C_P, latent heat, λ, density, ρ

Fig. 1 – The proposed Melting Rate Triangle.

Heat Source

The *'Heat Source'* side of the Melting Rate Triangle is concerned with all aspects that relate to the physical and chemical processes of burning within the attached liquid droplet, and is therefore the most complex and poorly understood of the three sides. This side represents the net rate of heat generation, which is the difference between heat generation and heat loss terms. Heat generation is estimated here as the product of fuel mass flow rate, extent of reaction and heat of combustion. Whilst fuel mass flow rate is easily characterized (it is simply the product of RRMI, density and rod cross-sectional area), the other two terms are more difficult to estimate. The Heat of Combustion is obtained experimentally or analytically (once an assumption is made regarding reaction chemistry) [10], and the extent of reaction is dependent on oxygen pressure, concentration, adsorption/absorption, solubility and transport (and, likely, other factors). Recent work by Suvorovs [11] indicates that extent of reaction is also a function of test specimen diameter. The presence of alloying elements, contaminants and/or catalysts is also known to affect the rate of heat generation. Heat loss occurs through bulk mass transport, especially dripping, which is gravity dependent. Heat is also lost to the surroundings, especially to the solid rod by conduction and convection, and this term is therefore dependent on the RRMI. All of these competing effects determine the effective droplet maximum temperature, T_D, which is identified as a critical parameter.

Heat Transfer

The *'Heat Transfer'* side of the Melting Rate Triangle is concerned with all aspects that relate to transferring thermal energy from within the burning droplet (where it is generated) across the SLI and into the solid rod (where it is dissipated). The key parameter T_D is critical in this process because it is the principal factor that determines (or *'drives'*) the heat flux that enters the

SLI surface. Heat flux input into the SLI is represented by the one-dimensional conduction equation, incorporating an effective heat transfer coefficient, κ_{eff}. This is assumed to capture the combined effects of both conduction and convection, as described by Steinberg and Wilson [12] and Wilson and Stoltzfus [13]. Heat flux is then integrated over the entire SLI surface area to determine the total heat transfer rate to the solid metal (although the simplifying assumption that heat flux is constant over the SLI is used). This highlights the importance of SLI surface area, because it limits the heat flux that can enter the solid rod. This side of the Melting Rate Triangle clearly shows that any factor that changes the three-dimensional shape (and, hence, area) of the SLI can alter the RRMI, such as sample orientation (as shown by Sato et al. [14]), test specimen cross-sectional shape (circular, rectangular, triangular, etc. as shown by Suvorovs et al. [15]), configuration (rod, sheet, mesh, etc.), surface finish (e.g. threaded), or gravity level [16-18]. Transient phenomena like precession in reduced gravity, characterized by random helical motion of the spherical molten droplet, also alter SLI surface area and RRMI in a similar way. The surface tension of the molten material at the melting temperature, T_M, (the temperature at the external boundary of the SLI) is noted because any change in SLI shape is dependent on surface tension forces (since it is the surface tension forces that act at the solid/liquid boundary to define and/or alter the SLI shape). In this way, heat transfer is modeled by taking the droplet temperature, T_D, obtained from the *'Heat Source'* side of the Melting Rate Triangle, using this to determine heat flux, and then integrating over the surface area of the SLI, A_{SLI}, which is the next key parameter.

Heat Sink

The *'Heat Sink'* side of the Melting Rate Triangle is concerned with the extent to which melting occurs as a result of heat transfer to the solid rod. Of the three sides, this is the most easily characterized, because the material properties of the solid are well known and heat transfer in a slender rod is almost entirely one-dimensional [19]. The total heat transfer rate is obtained from the product of heat flux and SLI surface area. As shown in Fig. 1, this can be related to the RRMI, υ_{RRMI}, by the rod cross-sectional area (or diameter squared for a circular cross-section), material properties and initial temperature. In some normal-gravity cases, when the SLI is planar and perpendicular to the rod centerline, the equation shown would simplify because $A_{SLI} = \pi\phi^2/4$, which is why this equation alone doesn't explicitly capture the dependency of RRMI on rod diameter. The dependence of RRMI on diameter is discussed in further detail in the following section. Importantly, the result is that the melting rate (represented by RRMI) is obtained, which, as the interpretation of the model continues, is linked back to the *'Heat Source'* step in the next iteration. This highlights the closed-loop nature of the model, whereby a change in one of the sides eventually feeds back, which is consistent with the inherent stability or *'self-control'* that many burning systems exhibit, for example, in that the RRMI often remains almost constant throughout a test.

Assessing the Melting Rate Triangle

An important requirement of a conceptual model, as noted by Wilson and Stoltzfus [13], is the need for it be both consistent with existing experimental data and capable of being expanded to incorporate new information. In this section, the Melting Rate Triangle is compared to well-known trends reported for the heterogeneous burning of metallic rods. These include the dependence of RRMI on the following: test material; oxygen pressure and concentration; gravity level, precession (in reduced gravity), sample orientation (except in microgravity); sample cross-sectional shape, configuration and initial specimen temperature.

- *Test Material* – Clearly, changing material properties such as density and heat of combustion will significantly affect all sides of the Melting Rate Triangle, especially *'Heat Source'* and *'Heat Sink'*, which would clearly result in a change in RRMI. A change in density, for example, will alter the energy requirement for melting (*'Heat Sink'* side) and the mass-flow rate of fuel into the droplet (for a given RRMI; *'Heat Source'* side). Altered heat of combustion will affect the rate of energy generation (*'Heat Source'*side). In this way, the Melting Rate Triangle demonstrates how altering the material properties will affect the rates of energy generation and dissipation, and how this is likely to influence RRMI.

- *Oxygen Pressure and Concentration* – The Melting Rate Triangle captures the effects of any change in oxygen availability in the *'Heat Source'* side, as this affects the extent of reaction and the overall energy release rate. For example, the Melting Rate Triangle predicts that a reduction in oxygen availability at the reaction zone will reduce the net rate of energy generation, causing a decrease in droplet temperature, T_D, (*'Heat Source'* side). The ensuing reduction in heat flux from the droplet to the solid, without any change in the *'Heat Sink'* energy requirements, causes the RRMI to decrease, which is consistent with the observed trend. RRMI, which sets the mass flow rate of fuel into the droplet, will tend to decrease until equilibrium is reached with a lower RRMI at which the melting rate can be sustained. In the limiting case, if the oxygen supply is completely removed, this rapidly decreases the energy generation rate in the '*Heat Source'* side of the Melting Rate Triangle and the RRMI will quickly tend towards zero; that is, fire propagation will cease.

- *Gravity Level, Precession (in reduced gravity), Sample Orientation (except in microgravity)* – These are all examples of changes in SLI surface area altering the heat transfer rate into the metal rod, causing a change in RRMI. In these cases, the Melting Rate Triangle captures the effect on RRMI in the *'Heat Transfer'* side. Each of these factors alters the interfacial geometry between solid and liquid phases (with no change in the energy requirement for melting and minimal changes in the net rate of energy generation in the droplet). This increases the available contact surface area for heat transfer, which increases the total heat transfer rate into the solid resulting in faster melting.

- *Sample Cross-Sectional Shape, Configuration* – Changes in sample cross-sectional shape were shown by Suvorovs et al. [15] to alter RRMI in a statistically significant way. RRMI values were compared for test specimens with circular, rectangular and triangular cross-sectional shapes but the same cross-sectional area. They reported differences in RRMI values that correlated (qualitatively) with the extent to which the SLI shape was altered due to the molten material climbing the sharp corners of the rectangular and triangular rods. The correlation between the change in SLI shape (and surface area) and RRMI was confirmed by Ward and Steinberg [7]. In the context of the Melting Rate Triangle, there is no difference in the *'Heat Source'* side, since the test conditions were held constant and there was no effect on droplet size or surface area, which means conditions within the burning droplet were likely unaffected by the change in rod cross-sectional shape. Further, there are no differences in the energy requirements for melting in the *'Heat Sink'* side, since the cross-sectional area was kept constant despite the change in shape. Therefore, by elimination, the Melting Rate Triangle indicates that the cause of the variation in RRMI is related to the *'Heat Transfer'* side. Close inspection of the test imagery reveals small differences in SLI shape that correlated with the observed change in RRMI. This clearly illustrates an analysis process in which the Melting Rate Triangle can be used to identify and clarify observed results, and also shows how the affects of geometric changes are modeled.

- *Initial Specimen Temperature* – The influence of specimen initial temperature on melting rate has been demonstrated by Sato and Hirano [20] and Engel et al. [21]. Rods with higher initial temperatures were shown to exhibit higher melting rates. This effect is captured in the *'Heat Sink'* side, whereby elevated initial specimen temperature reduces the amount of energy that is required to melt the solid material. So, for no changes in *'Heat Source'* or *'Heat Transfer'*, the altered energy requirement in the *'Heat Sink'* produces a change in RRMI.

These examples demonstrate that the model is consistent with existing data and provides a rigorous method for interpreting experimental results. It also provides a conceptual framework for the incorporation and analysis of new information as it becomes available, for example in further understanding the effect of test specimen diameter on RRMI. Recent work by Suvorovs [11] shows that as diameter increases, the molten droplet becomes *'flooded'* with unburnt metal, which reduces the extent of reaction and has the double effect of (a) reducing the amount of energy released by burning and (b) sinking energy into heating liquid metal that never burns. A lower extent of reaction at higher diameter was confirmed through analysis of quenched specimens. Captured in the *'Heat Source'* side of the Melting Rate Triangle, the influx of liquid metal absorbs energy within the molten droplet, and reduces the net amount of energy that is available to cause continued melting of the solid. This reduces the maximum droplet temperature, T_D, heat flux to the solid and the RRMI. Also, although the heat transfer surface area at the SLI increases (for larger rod diameters), this is offset by the increased requirement for melting. This means there is no net change in the *'Heat Transfer'* or *'Heat Sink'* sides of the Melting Rate Triangle and the dependency of RRMI on rod diameter is due to changes in the *'Heat Source'* parameters alone.

The Melting Rate Triangle can be used to investigate either quasi-steady self-sustained burning (such as global pressure or temperature dependencies) or transient phenomena. For example, as was discussed earlier, the Melting Rate Triangle may provide insight into the effects of large disturbances such as extinguishment by inert gas or immersion in water. These clearly affect the *'Heat Source'* side by reducing the availability of oxygen and/or increasing heat loss to the surroundings, breaking the feed-back cycle and causing a critical interruption of the melting process. In this way, the Melting Rate Triangle provides insight into the processes occurring during burning and, by extension, may also contribute to further understanding the *limits* of burning – ignition and extinguishment. The Melting Rate Triangle therefore provides a powerful tool for organizing, coupling, presenting and understanding the many competing factors that influence instantaneous RRMI during heterogeneous burning, thus creating a framework for analysis and discussion.

Applications

The Melting Rate Triangle concept may be extended to applications beyond standardized flammability testing of upward-burning cylindrical rods. This section discusses how the work is relevant to the application of standard flammability test results in an industrial context. Metal flammability is not an inherent material property, but is instead dependent on factors including specimen shape, size, composition, configuration and orientation, oxygen pressure and concentration, and many other parameters [3-6]. Metal flammability is therefore assessed experimentally in standardized tests, such as ASTM G124. However, given the dependence of flammability, of which RRMI is one indicator, on so many parameters, it is difficult to confidently apply the results of standard tests in an industrial environment. For example, in service applications under similar conditions to a standardized test (oxygen concentration, pressure, etc.), whilst this may imply similar burning characteristics on the *'Heat Source'* side of the Melting Rate Triangle, differences in geometry could result in significant changes in the *'Heat Transfer'* and '*Heat Sink'* processes and, hence, melting rate.

For example, burning liquid may interact differently with threaded surfaces compared to the smooth surface of a standard test specimen, altering the interfacial geometry and SLI for similar sized droplets and possibly affecting melting rate through a change in the *'Heat Transfer'* side of the Melting Rate Triangle. Any surface feature that facilitates increased contact between liquid and solid phases may increase the melting rate. The SLI geometry is also clearly different depending on whether the liquid is hanging freely from an exposed component or pooling in a cavity, which will also affect fire propagation. Local cross-sectional area, dependent on component size and global geometry, affects the energy requirements for melting, as shown in the *'Heat Sink'* side of the Melting Rate Triangle. For example, a burning droplet may extinguish if it lands on the flat surface of a large body (such as a valve body), but the same droplet may lead to significant fire propagation if it lands on a sharp edged feature (such as some internal valve components), where the energy requirements for subsequent melting and initial burning are smaller. In the context of industrial oxygen systems, this implies, for example, that components should be oriented with thin-walled features at the top, so that any molten material that lands on these surfaces will, due to gravity, form a freely-hanging droplet (instead of pooling), which would tend to minimise the contact area between liquid and solid phases, limiting the total heat transfer rate and making subsequent melting less favorable. In this example, the strategy for limiting fire propagation is to, despite the presence of a significant a *'Heat Source'* in the burning droplet and the lack of a large *'Heat Sink'* (due to the local thin cross-section), attempt to interrupt the melting cycle by using controllable geometric design parameters to restrict the *'Heat Transfer'* side of the Melting Rate Triangle. In this way, the Melting Rate Triangle provides insight into strategies to limit fire spread. Just as the Slusser and Miller "Extended Fire Triangle" [2] implies that ignition can be avoided by removing one of the three legs, the Melting Rate Triangle implies that RRMI can be reduced or, perhaps, even stopped (reduced to zero) by limiting or interrupting one of the three processes. The Melting Rate Triangle shows that, even in the presence of a *'Heat Source'*, such as the case when a fire occurs inside an oxygen system, the melting rate can be reduced by limiting the extent to which the melting *'potential'* is realized, by restricting the *'Heat Transfer'* process and increasing the *'Heat Sink'*. This relates especially to the design of thin-walled or sharp-edged features, threaded surfaces, meshes, linkage rods and other small valve components.

Summary

The Melting Rate Triangle provides a framework for discussion and enables further understanding of the net effect of the competing influences of multiple known (and unknown) parameters that are relevant to the heterogeneous burning of metallic materials. It enables a holistic view of the burning system and contributes to an improved understanding of how different parameters interrelate and affect the burning process under different conditions. The Melting Rate Triangle was shown to be consistent with existing experimental data and known trends, and capable of incorporating new information. Application of the Melting Rate Triangle provides insight into the results of standardized flammability tests and may improve the process of using these results in the design and analysis of practical oxygen components and systems in industrial scenarios.

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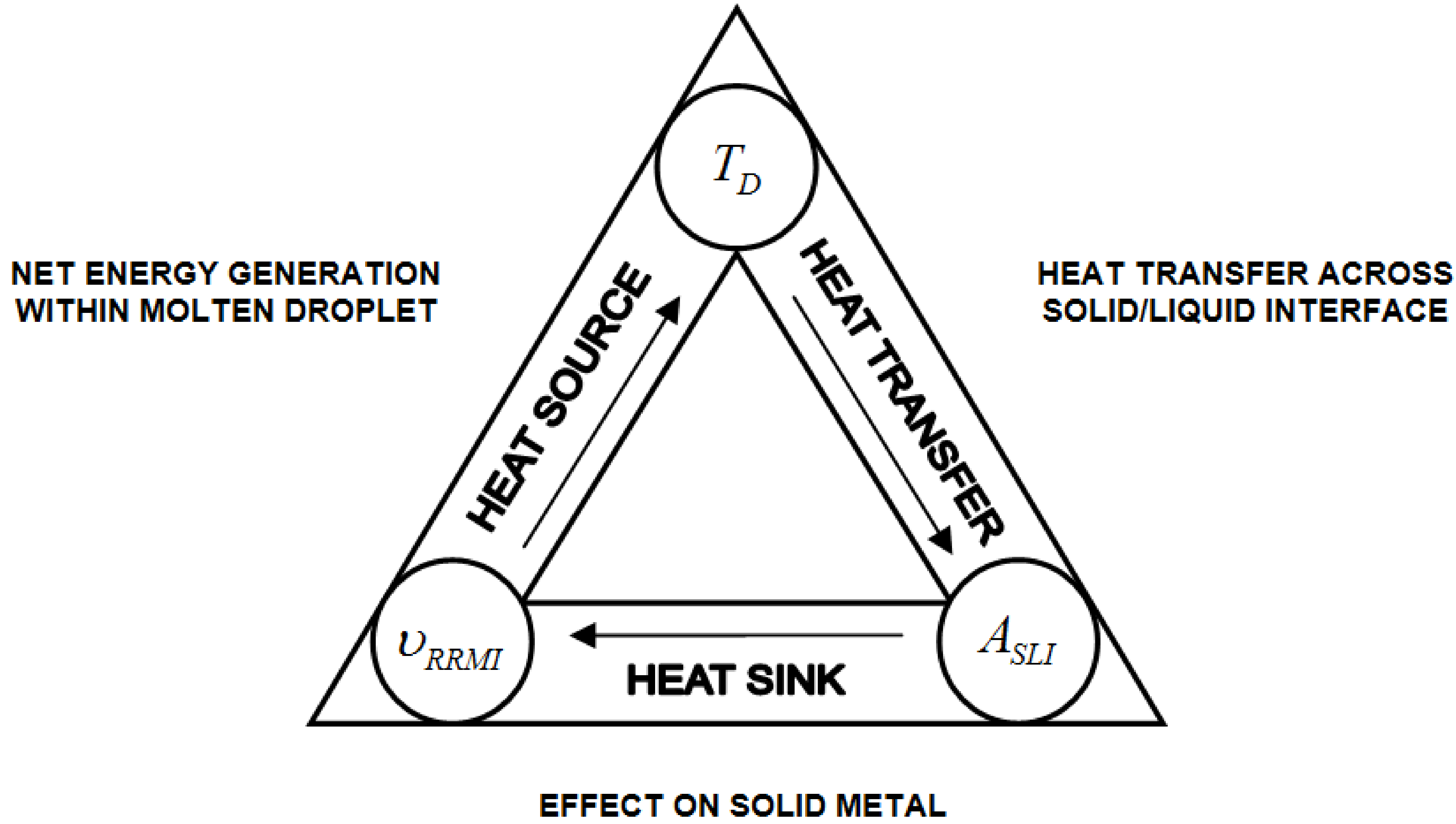

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		Heat Loss: • Bulk transport (dripping) • Loss to surroundings
HEAT TRANSFER	Heat flux from molten droplet, $\dot{q}$	$\dot{q} = \frac{\kappa_{eff}}{L}(T_D - T_M)$ • Solid melting temperature, T_M • Effective heat transfer coefficient between droplet and solid, K_{eff} • Heat transfer path length within droplet, L
	Solid/Liquid Interface (SLI) Shape and Surface Area, A_{SLI}	In some cases, $A_{SLI} \neq S$, consider: • Orientation (except in microgravity) • Cross-section shape • Surface finish (threaded, etc.) • Configuration (sheet, rod, mesh) • Gravity level • Precession, helical motion (in microgravity)
HEAT SINK	**Regression Rate of the Melting Interface, υ_{RRMI}** (melting rate)	$\upsilon_{RRMI} = \frac{\dot{q}}{[\rho \cdot (C_P(T_M - T_0) + \lambda)]} \cdot \frac{A_{SLI}}{S}$ • Initial temperature, T_0 • Cross-sectional area, S • Surroundings and boundary conditions • Specific heat, C_p, latent heat, λ, density, ρ